Trends in Industrial Electric Motor Usage and Potential Impact on Energy Consumption

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EEA Conference & Exhibition 2012, 22 - 20 June, Auckland

1 Review and Interpretation of the Trends

The tutorial summary [1] presented in 2005 by IEEE Life Fellow B.K. Bose shall be adopted as a broad thesis identifying trends and usages in electrical machines, which outlines as follows:

1. Machine evolution has been slow and sustained over the last 100 years.
2. Advanced CAD programs and improved materials have contributed to lower cost, higher efficiency, improved reliability and power density.
3. Brushed DC machines will tend to be obsolete in the future.
4. Cage type induction motors remain industry's workhorse in a wide power range.
5. Wound Field Synchronous Machines (WFSM) remains popular in very high power applications.
6. Permanent Magnet (PM) synchronous machines are efficient but at higher cost – they are superior to induction machines in life cycle cost.
7. Most machines (for constant or variable speed drive) will have front end converters in the long run.
8. Intelligent machines with integrated converter and controller look very promising in the future

With regard to DC machines, Bose elaborates further in [2] that traditionally AC machines have been used for constant speed applications, and dc machines for variable speed drives. However, the advent of solid-state variable-frequency inverters since the 1960's, and the later progression of power semiconductor devices, various converter topologies, advanced PWM techniques, and improved control and estimation methods gradually brought high performance AC drives of various types into the market place, pushing DC drives towards obsolescence.

That cage type induction motors are industry's workhorse is widely confirmed across the literature [3,4]. Bose also summarizes trends of induction motor drives [1]:

1. Voltage-fed converter cage machine drives are the most commonly used industrial drives today – also the trend for the future.
2. Future emphasis on converter and controller integration with the machine on the lower end of the power range – intelligent machines.
3. Open loop volts/Hz control is very popular for general purpose industrial drives, whereas vector control is used in high performance drives.
4. Vector control will be universally used in the future.
5. Increasing emphasis of variable frequency soft starting of constant speed motors.
6. Increasing emphasis on speed sensorless vector and scalar drives – however precision speed estimation, particularly at zero frequency remains a challenge.
7. There will be increasing emphasis on on-line drive diagnostics and fault tolerant control to improve system reliability.

Bose [2] argues that for constant speed induction motor applications, the variable frequency starter has the advantages of full torque starting and sinusoidal line current compared to the traditional thyristor based phase-controlled starter. He states that as the converter cost decreases, eventually variable speed starters will be extensively used. Presumably these would be standard converter topologies designed with thermal ratings specified only for starting, which would be switched out once the motor was running up to speed.

Over the past 30 years [4] states that there have been clear trends in motor utilization that demand higher energy efficiency and a reduced total cost of ownership. Induction motors have been able to incrementally improve energy efficiency to satisfy requirements. In the US both mandatory standards (US Energy Policy Act – EPAct, effective 1997) and voluntary standards (NEMA Premium) have been applied to general purpose induction motors [4]. The use of cast copper rotors in place of aluminium for medium size ratings has been considered [4,5].

In [6] the case for using the Pole Amplitude Modulated (PAM) induction motor is presented for reducing initial and operating costs in the petroleum and chemical industries. They note that Variable Speed Drives (VSD) are used with large induction motors in applications such as pumps, fans, mixers, and compressors allowing the power consumption to be reduced at lower operating speeds. However, the initial cost of the VSD and its operating power losses need to be considered. As an alternative to using a VSD, induction motors having a consequent pole winding have been used providing two speeds, but these only allow a speed ratio of 2:1. Other two speed machines exist where two independent windings, one for each desired speed are wound into the stator to accomplish different speeds other than 2:1. The latter type of motor requires more space in the stator to accommodate the dual windings making the machine larger, less efficient and more expensive. In contrast the PAM motor is a two speed single winding machine that can accomplish two speeds at different speed ratios. This is achieved by reversing the current flow through portions of the windings via winding connections, to modulate the original rotating field to create sum and difference frequencies. The authors mention that a typical induction motor efficiency ranges from 93% to 97% when operated at full load, while a VSD has a typical efficiency ranging between 96% and 98%. They compare electrical losses between PAM motor and VSD/motor cases for power ratings ranging between 3500 HP and 11,000 HP. The PAM motor efficiencies are similar to those of the normal induction motors, and so the VSD system losses are simply larger by an amount corresponding to the converter. In the cases presented the additional losses due to the converter range between 136-236 kW. They claim that starting a PAM motor with the low speed connection of the winding reduces the starting current inrush by up to 30% compared to a single speed motor. A second current inrush occurs when the winding connection is changed to high-speed, however this is lower than it would be if the rotor was started from standstill. PAM motors were developed in the 1950's, and can offer better overall operating efficiency than a converter-motor combination if only two-speeds rather than full variable speed is required.

Wound-rotor induction motor drives with slip power recovery (static Kramer and Scherbius drives) have been used in limited speed range for large pumps, compressors, variable speed hydro, flywheel energy storage, and modern wind generation systems [2]. Although the machine cost is somewhat higher along with the disadvantage of slip rings and brushes, the converter cost is somewhat economical. This type of drive is expected to be obsolete in the future [2].

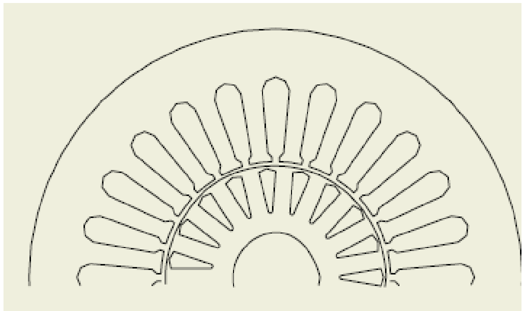
For synchronous motor drives, Bose summarizes his outlook on trends [1]:

1. Synchronous motors have higher efficiency – but are more expensive than induction motors i.e. life-cycle cost is lower.
2. WFSM are popular in the highest power range because of improved efficiency and economical converter system due to unity or near unity leading power factor.
3. Declining cost of NdFeB permanent magnets will make Permanent Magnet Synchronous Motor (PMSM) drives more popular in the future – eventually surpassing induction motor drives.
4. Surface Permanent Magnet (SPM) machine drives are used in the constant torque region whereas Interior Permanent Magnet (IPM) machine drives can be used into field-weakening extended speed operation.
5. Trapezoidal SPM machine drive is truly analogous to the (brushed) DC drive.
6. Many advanced control and estimation techniques for induction motors are also applicable for synchronous motors.
7. Switched reluctance drives have a questionable future except in specialized applications.

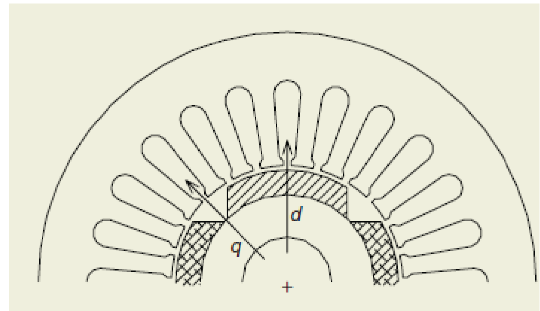
Unlike induction motors, synchronous motors are not self-starting unless they also contain a rotor induction cage. Even with a cage, the starting torque of a line-starting PM motor, which will have interior rotor magnets, will be poorer than that of an induction motor due to an asynchronous braking torque caused by the PM field. Thus, in general, brushless PM motors are required to be converter driven machines and will be variable speed. PM motors are more efficient than induction motors. Identifying the trends in PMSM drives is therefore important.

Bose's assertion [1] that PMSM drives will surpass induction motor drives needs to be examined. Electromagnetic scaling laws increasingly favour current excitation over PM excitation in terms of copper versus PM volume as a machine gets larger [7]. At a certain threshold of machine size, the volume of copper required to produce a given field excitation will be less than that of a PM. Where the economic threshold lies choosing between the two (i.e.wound field or PM rotor) is determined by the relative cost of high-energy magnets to copper. The PM machine is likely to be more expensive, but this may not be the case when electricity tariffs and life-cycle cost are also accounted for as there is no field excitation energy required. Operationally, a PM machine with a short circuit fault may have a large braking torque. In contrast, a conventional synchronous machine can be de-excited under fault conditions, and the induction motor is self-protecting. Magnets can be susceptible to demagnetization due to faults or overheating, and to corrosion. However, due to dramatic improvements in the magnetic and thermal properties of PM materials over the past 20 years, along with considerable cost reduction, PMSM motors represent viable alternatives.

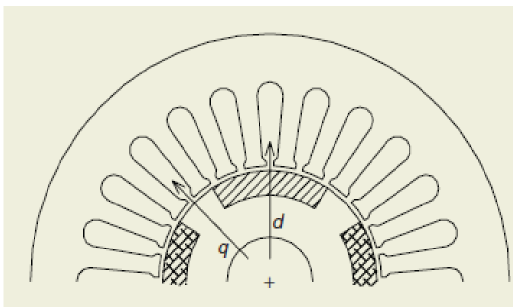
A variety of PM rotor configurations are possible which can be used in a PMSM drive. Principal configurations are described in [4] and are accompanied with basic explanations in the text. These configurations are reproduced in Figure 1. The IPM rotor shown in Figures 1(b)-(f) is suitable for high performance variable speed drives. The magnetic characteristics of the IPM rotor allow a wide constant-power speed range which is required in many industrial applications. The IPM construction is reasonably mechanically robust, can allow sensorless rotor detection, and also affords the magnets some thermal and de-magnetization protection from the stator windings.



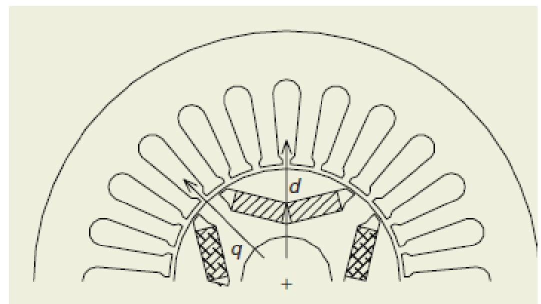
(a) Induction motor



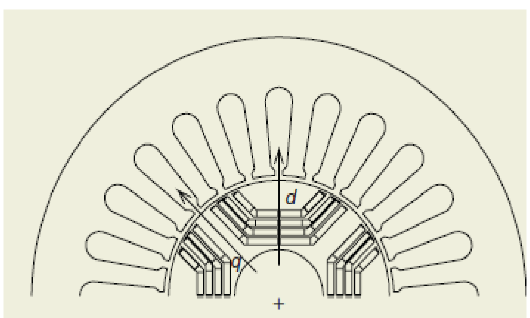
(b) Surface PM motor



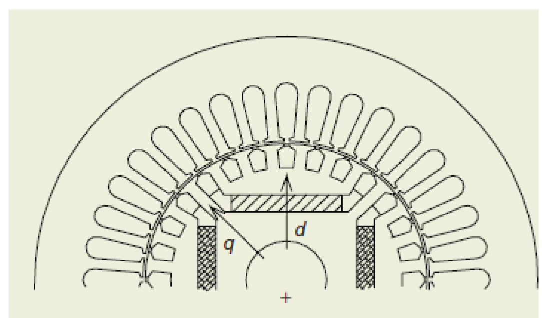
(c) Surface PM motor with teeth between magnets to create rotor saliency



(d) Interior PM motor with rotor saliency via a single flux barrier



(e) Interior PM motor with multiple flux-barrier rotor saliency (also referred to as PM Assisted Synchronous Reluctance Motor)



(f) Line-start interior PM motor with induction cage

Figure 1 Common lamination and rotor configurations for brushless PM motors, as well as a typical induction motor, reproduced from [4].

Standard PMSM drives up to 300kW were available from at least 2004 onwards [3], and clearly PM machines are being used in much higher power levels for wind generation and ship propulsion. In [3], which was published in 2004, it was suggested in the low power range of 2-10 kW that the PMSM, as an inverter motor, may be dominant within the next decade. So has this happened? In [3] induction motors were noted as having a high efficiency at the medium power level so the most promising economical power range for PM motors was assumed to be below 10 kW. But this view is changing; in [4, published in 2008] it was anticipated that PMSM motor availability will soon expand to cover a significant portion of medium-horsepower applications in the petrochemical industry. In [8], to be published in 2011, it is remarked that only recently has industry considered IPM drives as a competitor of induction drives for mass production. Bose's assertion will be qualified in this paper by suggesting that PMSM drives may surpass induction motor drives eventually but only gradually. The impact will be greatest in the LV lower power ranges, but have a lessening impact beyond this.

But for constant speed applications, an induction motor is not burdened by the extra cost and losses of a converter, and so it remains highly competitive.

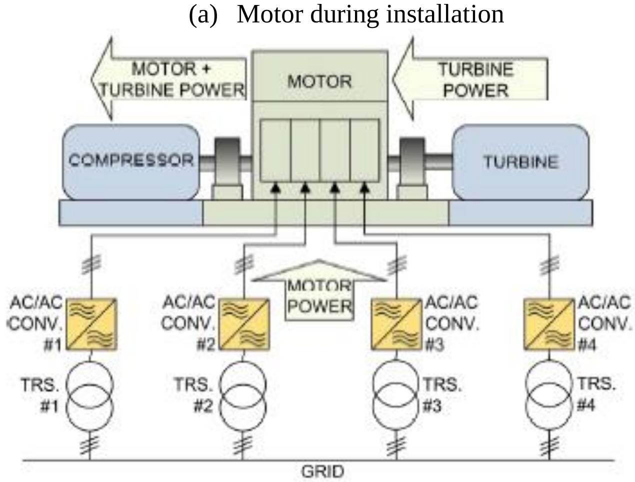
The Switched Reluctance Motor (SRM) is noted in [2] as receiving attention in the literature. It is simple and extremely rugged in construction having salient laminated iron poles on both the rotor and stator. It only requires uni-directional currents thereby simplifying converter design. It relates closely to stepper motors, and as such is a digital or electronic machine rather than a synchronous one, employing pulsed rather than continuous sinusoidal currents. It cannot operate without its converter. An SRM drive is economical, but has inherent pulsating torque and acoustic noise problems, generally requires an absolute position encoder, and is unlikely to be more efficient than a PMSM drive. Bose's view on SRM's that they have a questionable future is thus justifiable.

In the very high power range, Load Commutated Inverter (LCI) wound field synchronous motor drives are very popular because of simple thyristor–based converter topology and improved system efficiency [2]. However, recently voltage-fed multilevel converters are finding almost universal acceptance for large-power four-quadrant induction and synchronous motor drives, replacing traditional thyristor-based cycloconverters and current-fed converters [2].

High Temperature Superconducting (HTS) synchronous motors are proposed in [9] for industrial applications. Motor losses and weight are predicted to be reduced by a factor of two in comparison to high efficiency induction motors above 5000 HP. These HTS motors are expected to be converter fed and variable speed with rotating cryogenically cooled HTS field windings. The authors assert that to be economical, cheaper second generation HTS wire will be required. They mention that, at the time of their publication in 2006, the largest 2nd generation HTS motor demonstrated was rated at 7.5 HP. Rotor cool down before operation can begin on a large HTS motor would take three days. It is suggested in this paper that issues of initial cost, ruggedness, and reliability will impede the adoption of HTS motors.

Multiphase machines [10, 11], of both synchronous and induction types, have experienced substantial growth in interest so far this century. An increasing number of induction motors are not connected directly to three-phase supplies. Instead, they derive their power from a converter which itself is connected to the three-phase supply. The output stage of the converter and the motor must have the same number of phases. However, there is no technical reason why more than three phases should not be used. In practice three-phase motors are traditionally used because of low mass-production costs and standardisation. But a multiphase machine produces a field with a lower space-harmonic content, so that the efficiency is higher than a three-phase machine. Fault tolerance is also higher. Multiphase machines are less susceptible to time-harmonic components in the excitation waveform which lessens pulsating torques. Using a multiphase motor also allows the possibility of reducing the rating of power electronic components as the power is distributed over more phases, which is an issue of huge significance in high power drives. Noise is also improved. All of these advantages are cited as making multiphase machines ideal for direct drives in marine applications. Multiphase machines are currently being used where both the machine and its control electronics are designed as a system, rather than as individual components. An impressive example of this is applied in the oil & gas industry in which a specially designed 45 MW 12-phase synchronous machine is fed by four PWM multilevel Voltage Source Inverters [12], shown in Figure 2.

(a) Motor during installation



(b) Schematic of the motor as part of a LNG refrigeration string

Figure 2 45 MW 12-phase synchronous machine fed by four PWM multilevel Voltage Source Inverters, reproduced from [12].

2 Potential Impact on Electrical Energy Consumption in New Zealand

According to [13], the European community has set up an energy saving target of 20% of current consumption by 2020. Worldwide, the desire to reduce carbon emissions and the introduction of efficiency regulations and carbon taxes will have an impact on electric motor trends and usage. In [13] a calculation is presented showing that in Germany if the efficiency of half of all motors installed in industrial drives is increased by 4%, this will save only 1.4% of all German industrial electrical energy usage. By changing fixed speed drives to variable speed drives but only where variable speed provides an energy saving advantage at partial load such as in a pump, fan or compressor application, a much higher energy saving potential is possible. In Germany the pump sector dominates industrial drive applications. An 8% energy savings is estimated for using variable speed drives. The biggest energy saving potential is provided by optimization of the whole drive system, comprising not only the motor and electrical components, but also the 'load machine'. This involves reducing moving masses, avoiding mechanical elements such as couplings, additional shafts, and gears. An astounding 20% reduction in German industrial electrical energy consumption is predicted for optimization of the whole drive system.

Industrial and Agricultural Sectors	Delivered Energy (TJ)
Basic Metals Industries	23,560.29
Chemicals, Related Products and Plastics	3,320.61
Concrete, Clay, Glass and Related Minerals Manufacture	871.675
Dairy Agriculture	4,118.83
Dairy Products	2,858.94
Fabricated Metal Products, Machinery and Equipment	1,406.32
Forestry and Logging	341.54
Indoor Cropping	16.843
Mining and Quarrying	1,173.07
Non-Dairy Agriculture	1,235.12
Other Food Processing Sectors	2,226.09
Other Manufacturing Industries	197.81
Paper and Paper Products, Printing and Publishing	5,656.15
Slaughtering and Meat Processing	2,672.42
Textile, Apparel and Leather goods	593.146
Transport and Storage	2,511.78
Wood Processing and Wood Products	7,479.63
Total	**60,240.25**

Table 1 NZ electrical energy delivered by industrial and agricultural sectors for the year ending March 2007, sourced from [14].

According to [14], 97% of medium voltage (MV) motors were not controlled by variable speed drives in 1998. The majority of MV motors are used to control fluid flow in pump, fan, and compressor drives. If these MV motors were able to operate at variable speed with throttle fully open, efficiency improvements up to 30% at light load could be obtained [2].

An estimate of the potential New Zealand electrical energy savings that could be obtained by optimization of whole electromechanical drive systems in the industrial and agricultural sectors is made as follows. Using data sourced from [15] for delivered electrical energy in New Zealand for the year ended March 2007, industrial and agricultural sub-categories and their delivered energies are listed in Table 1, giving a combined total of 60,240.25 TJ. In Table 2, energy delivered for Aluminium production in the same period is subtracted from this total, as the energy conversion process is electro-chemical for Aluminium production. In Germany, 69% of industrial electrical energy is consumed by drives, with 26% used for heating, and 5% for lighting [13]. Assuming in the NZ industrial and agricultural sectors that 69% of electrical energy is also used in electromechanical drives, Table 2 shows that 8.19 TWh of electrical energy is consumed by drives in these sectors. By then assuming that on average 10% of this consumed energy may be saved via whole drive system optimization, 0.82 TWh of energy may be saved. This is equivalent to approximately 2.1% of total NZ electrical energy consumption or an equivalent annualized power of 94 MW. This saving compares to the capacity of the Te Apiti Wind farm (91 MW) or the capacity of the Whakamaru hydro station (100 MW) [16].

	Delivered Energy (TJ)	(TWh)	% of total NZ electrical consumption	Equivalent annualized power (MW)
Sum of industrial and agricultural electrical energy	60,240.25	16.73	43.6	1,910
Less Al2O3 reduction (i.e. excluding aluminium production)	42,755.76	11.88	31.0	1,356
Assuming 69% consumed by electromechanical drives	29,501.47	8.19	21.4	935
Assuming 10% saving via whole drive system optimization	**2,950.15**	**0.82**	**2.1**	**94**

Table 2 Estimate of potential electrical energy saving in NZ industrial and agricultural sectors by optimization of whole electromechanical drive systems, based on consumption for the year ending March 2007 shown in Table 1.

3 Conclusions

Cage type induction motors remain industry's workhorse in a wide power range. Where there is an energy saving advantage to be gained from variable speed operation, variable speed induction drives will be rapidly adopted. For constant speed applications, induction motors will remain highly competitive. The synchronous motor will remain the other dominant motor type in motor usage. In the rapidly growing variable speed area, permanent magnet motors may gradually gain acceptance in preference to induction machines in the low to mid power ranges due to higher efficiency and lower life cycle cost. Voltage-fed multilevel converters are finding almost universal acceptance for large-power four-quadrant induction and synchronous motor drives. Multiphase machines (having more than three-phases) of both induction and synchronous types will be increasingly used in high-power where both the machine and its control electronics are designed as a system, rather than as individual components.

In all cases, energy savings are obtained by improving drive system efficiency in three ways: first by motor efficiency, secondly by using a variable speed drive only where variable speed provides an energy saving advantage such as in a pump, fan or compressor application. Thirdly, by improving the efficiency of the load machine by, for example, reducing moving masses and mechanical couplings. For New Zealand's agricultural and industrial sectors excluding aluminium production, assuming that 69% of the electrical energy is consumed by electromechanical energy conversion, an average whole drive system optimization of 10% would yield an annual saving of 0.8 TWh or 2% of national electricity generation.

References

[1] B. K. Bose, ''Tutorial – Power Electronics and Motor Drives – Technology Advances, Trends and Applications," in *IEEE Int. Conf. on Industrial Technology*, 2005, pp. P20-P64.
[2] B. K. Bose, ''Power Electronics and Motor Drives – Recent Progress and Perspective, "*IEEE Trans. on Industrial Electronics*, Vol. 56, No. 2, Feb 2009, pp. 581-588.
[3] F. Blaabjerg, P. Thoegersen, "Adjustable Speed Drives – Future Challenges and Applications," in *4th Int. Power Electronics and Motion Conf.*, Vol. 1, 2004, pp. 36-45
[4] M. Melfi, S. Rogers, S. Evon, B. Martin, ''Permanent Magnet Motors for Energy Savings in Industrial Applications, "*IEEE Trans. on Industry Applications*, Vol. 44, No. 5, Sept/Oct 2008, pp. 1360-1366.
[5] A. Boglietti, A. Cavagnino, L. Ferraris, M. Lazzari, ''Energy-Efficient Motors, "*IEEE Industrial Electronics Magazine*, Dec 2008, pp. 32-37.
[6] J. Portos, M. Reddy, D. Eaton, "Application and Advantages of PAM Multi Speed Motors in Petroleum and Chemical Industries," in *Petroleum and Chemical Industry Conf.*, 2010, pp. 1-10.
[7] T. J. E. Miller, "*Brushless Permanent-Magnet and Reluctance Motor Drives"*, Clarendon Press, Oxford, 1989.
[8] M. Barcaro, N. Bianchi, F. Magnussen, ''Permanent Magnet Optimization in Permanent Magnet Assisted Synchronous Reluctance Motor for a Wide Constant Power Speed Range," *IEEE Trans. on Industrial Electronics,* 2011, to be published.
[9] R. Schiferl, A. Flory, W. Livoti, S. Umans, "High Temperature Superconducting Synchronous Motors: Economic Issues for Industrial Applications," in *Petroleum and Chemical Industry Conf.*, 2006, pp. 1-9.
[10] E. Levi, R. Bojoi, F. Profumo, H. Toliyat, and S. Williamson, ''Multiphase induction motor drives – a technology status review, "*IET Electric Power Applications*, Vol. 1, No. 4, 2007, pp. 489-516.

[11] E. Levi, ‘’Guest Editorial – Special Section on Multiphase Machines and Drives,“ *IEEE Trans. on Industrial Electronics*, Vol. 55, No. 5, May 2008, pp. 1891-1892.
[12] A. Tessarolo, G. Zocco, C. Tonello, “Design and Testing of a 45-MW 100-Hz Quadruple-Star Synchronous Motor for a Liquefied Natural Gas Turbo-Compressor Drive,” in *SPEEDAM 2010: Int. Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 2010, pp. 1754-1761.
[13] A. Binder, “Potentials for Energy Saving with Modern Drive Technology – a Survey,” in *SPEEDAM 2008: Int. Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 2008, pp. 90-95.
[14] S. Malik, D. Kluge, “ACS 1000 – World’s First Standard AC drive for Medium-Voltage Applications,” *ABB Review*, Vol. 2, 1998, pp.4-11.
[15] Energy Efficiency and Conservation Authority (2012), *Energy end use database*, [Online], http://www.eeca.govt.nz/energy-end-use-database
[16] Ministry of Economic Development (2012), *Energy data file 2011*, [Online], p. 111, http://www.med.govt.nz/sectors-industries/energy/energy-modelling/publications/energy-data-file/new-zealand-energy-data-file-2011